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Wood waste decomposition in landfills: An assessment of current knowledge and implications for emissions reporting

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ABSTRACT

Large quantities of wood products have historically been disposed of in landfills. The fate of this vast pool of carbon plays an important role in national carbon balances and accurate emission reporting. The Republic of Ireland, like many EU countries, utilises the 2006 Intergovernmental Panel on Climate Change (IPCC) guidelines for greenhouse gas reporting in the waste sector, which provides default factors for emissions estimation. For wood products, the release of carbon is directly proportional to the decomposition of the degradable organic carbon fraction of the product, for which the IPCC provides a value of 0.5 (50%). However, in situ analytic results of the decomposition rates of carbon in landfilled wood do not corroborate this figure; suggesting that carbon emissions are likely overestimated. To assess the impact of this overestimation on emission reporting, carbon decomposition values obtained from literature and the IPCC default factor were applied to the Irish wood fraction of landfilled waste for the years 1957–2016 and compared. Univariate analysis found a statistically significant difference between carbon (methane) emissions calculated using the IPCC default factor and decomposition factors from direct measurements for softwoods ($F = 45.362$, $p = <.001$), hardwoods ($F = 20.691$, $p = <.001$) and engineered wood products ($U = 4.726$, $p = <.001$). However, there was no significant difference between emissions calculated using only the in situ analytic decomposition factors, regardless of time in landfill, location or subsequently, climate. This suggests that methane emissions from the wood fraction of landfilled waste in Ireland could be drastically overestimated; potentially by a factor of 56. The results of this study highlight the implications of emission reporting at a lower tier and prompts further research into the decomposition of wood products in landfills at a national level.

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1. Introduction

With an ever-growing global focus on climate change mitigation, incentive has been placed on the accurate accounting and reporting of greenhouse gas (GHG) emissions to facilitate in setting goals for future abatement strategies. GHG accounting in the waste sector, which has historically been reliant on the disposal of solid waste in landfills, is often challenging as direct emissions are not measured, but rather calculated using emission modelling. In accordance with the Kyoto protocol, the majority of European countries use the 2006 IPCC Guidelines for National GHG Inventories (Eggleston et al., 2006) to estimate GHG emissions from the waste sector, including emissions from landfills. This estimation is based on tiered accounting methods. Tier 1 provides IPCC default data to countries with little data available and is the most inaccurate. Tier 2 includes first-order decay (FOD) equations with some default parameters defined by the IPCC, while Tier 3 is based on FOD equations with nationally developed parameters, such as the degradable organic content (DOC) of the waste and the fraction of the DOC that decomposes (DOC_f). In Ireland, and many other EU countries, emissions from landfills are calculated at the Tier 2 level (Duffy et al., 2011, Donlan et al., 2012) where IPCC default factors are employed and thus the accuracy of the results are reduced (IPCC, 2001). For methane (CH_4 emissions from landfills, the CH_4 generation potential is estimated from the amount of DOC in a solid waste landfill (by waste stream), the DOC_f, the CH_4 correction factor (MCF), and the fraction of CH_4 in generated landfill gas (F). The DOCf factor plays an important role the amount of CH_4 emitted, however this value is highly uncertain, particularly for wood products (Barlaz, 2004).

The major biodegradable components of wood products are cellulose and hemicellulose and under anaerobic conditions in landfills, their decomposition results in the generation of approximately equal volumes of biogenic CO_2 and CH_4 (Barlaz, 2006). However, the presence of lignin can interfere greatly with

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cellulose and hemicellulose degradation and research has shown that wood is very resistant to decay in landfills because its cellulose and hemicellulose is embedded in a matrix of lignin (Ham et al., 1993, Wang et al., 1994); the extent of which is highly variable. Consequently, the IPCC allocated DOC_f factor of 0.5 (50%) for wood products in landfilled waste, is potentially a gross overestimation. Early studies on carbon loss, suggest that 56% (DOC_f, 0.56) of the C in wood would be lost in landfills (Bingemer and Crutzen, 1987); providing an estimate similar to that provided by the IPCC. However, these measurements were based on stoichiometric calculations as opposed to direct analysis. In contrast, Bogner (1992) observed that CH_4 generation data from laboratory-based experiments under optimised conditions often overestimate actual CH_4 production in landfills as a whole. In corroboration of this, research by Micales and Skog (1997) reviewed estimated CH_4 yields from processes involved in anaerobic decomposition of forest products in landfills and suggested much lower levels of carbon decay (0–3%) than proposed by the IPCC. This suggests that a significant portion of the biogenic C in wood products does not decompose, and therefore represents a sink of C storage in landfills (Eleazer et al., 1997, Wang et al., 2011a,b, Barlaz, 2004, Barlaz, 1998). This decomposition, or lack thereof, will not only have an effect on the landfill C balance (Christensen et al., 2009), but may also have an impact of emission reporting at a national level.

Total European emissions from waste are estimated to be approximately 2% of total GHG emissions per year and in 2014 alone approximately 460,000 tonnes of wood waste was diverted to landfills (EUROSTAT, 2014). In the Republic of Ireland, the waste sector accounts for 2.5% of national emissions (above the EU average); with landfills contributing approximately 80% of this total (EPA, 2014). Consequently, the potential inconsistency between decomposition factors of wood products in landfills is an area of warranted investigation and its importance in both national and global C balances should not be overlooked.

The objective of this paper was to identify research on the decomposition of lignin containing wastes, particularly wood, in landfills and consolidate the calculated C decomposition rates for emission modelling. Using the Republic of Ireland landfill data for the years 1957–2014, a CH_4 emission inventory was established and statistical analysis was undertaken to elucidate differences in CH_4 emissions under differentiated decomposition factors from literature and the IPCC. This research aims to solidify the importance of accurate C reporting with high quality specific data (higher tier) and provides support for future research into the decomposition of wood products in landfills.

2. Methods

2.1. Systematic literature review

To identify wood product decomposition rates within the literature, a review protocol was developed where the pre-defined inclusion criteria were as follows: (1) direct results from defined landfill sampling sites, (2) comparative analysis of waste fractions in landfills, (3) laboratory simulations of wood products in landfills and (4) studies published in the English language from January 1st, 1990 to January 1st, 2016, inclusive. Studies were limited to full articles published in peer-reviewed journals and national reports by governmental agencies. Unpublished work, defined as master's theses, dissertations and abstracts from conference proceedings were not included. The rationale for this decision was based on the work of Van Driel et al. (2009) who concluded that (1) the difficulty in retrieving unpublished work could lead to selection bias, (2) many unpublished studies are eventually published, (3) the methodological quality of such studies are poorer than those that are published, and (4) the effort and resources required to obtain unpublished work may not be warranted. This approach is consistent with recent practice. Literature for inclusion was identified using four bibliographic databases (PubMed, Science Direct, Scopus and Google Scholar) using combinations of key terms (i.e. Wood(s), Forest(s), Waste(s), Landfill, Carbon, Greenhouse Gases, Decomposition). All literature scans were undertaken using Boolean positional operators ("AND", "OR", "SAME", "WITH") to focus literature searches. The research assessed was screened by assessing each publication (year, title, abstract) based on the explicit eligibility criteria. The systematic flow of the employed review process and quantification of studies across the flow chain is shown in Fig. 1.

2.2. Wood data collection

Total landfill waste tonnages were obtained from the Irish Environmental Protection Agency (EPA) Landfill gas survey upon request. Data were extracted for all licensed landfills in Ireland between the years 1957–2014. For quantification of the wood fraction of the waste, an estimation of 6.6% was applied based on an a European Commissioned report examining Waste (Villanueva et al., 2010); accurate waste characterisation of landfilled waste is not available for Ireland, particularly prior to the introduction of the European Landfill Directive in 1999.

2.3. Methane emissions inventory

For comparison of derived GHG emissions under different DOC_f values, the IPCC waste model (excel) was utilised to quantify CH_4 emissions, specifically. Within the model, CH_4 emissions from landfills for a single year are derived using the following equation:

$$CH_4 \text{ emissions} = \left[\sum_x CH_4\ generated_{x,T} - R_T\right] \times (1 - OX_T), \quad (1)$$

where

CH_4 emission = CH_4 emissions in year T, Gg;
T = inventory year
x = Waste category or material (Wood fraction);
R_T = Recovered CH_4 in year T, Gg; and
OX_T = oxidation factor in year T (Fraction).

The OX is the amount of CH_4 from the landfill that is oxidized in the soil or other material covering the waste. The amount of CH_4 generated from decomposable material in year T is estimated using the First Order Decay (FOD) of the mass of decomposable organic carbon (=DDOCm, Gg) in each waste category or type/material as follows:

$$CH_4 \text{ generated}_T = \text{DDOCm decomp}_T \times F \times 16/12 \quad (2)$$

where

DDOCm $decomp_T$ = DDOCm decomposed in year T, Gg;
F = fraction of CH_4 by volume in generated landfill gas (fraction); and
16/12 = molecular weight ratio between methane and carbon (ratio).

$$\text{DDOCm decompT} = \text{DDOCma}_{T-1} \times (1 - e^{-k}) \quad (3)$$

$$\text{DDOCmaT} = \text{DDOCmdT} + (\text{DDOCma}_{T-1} \times e^{-k}) \quad (4)$$

where

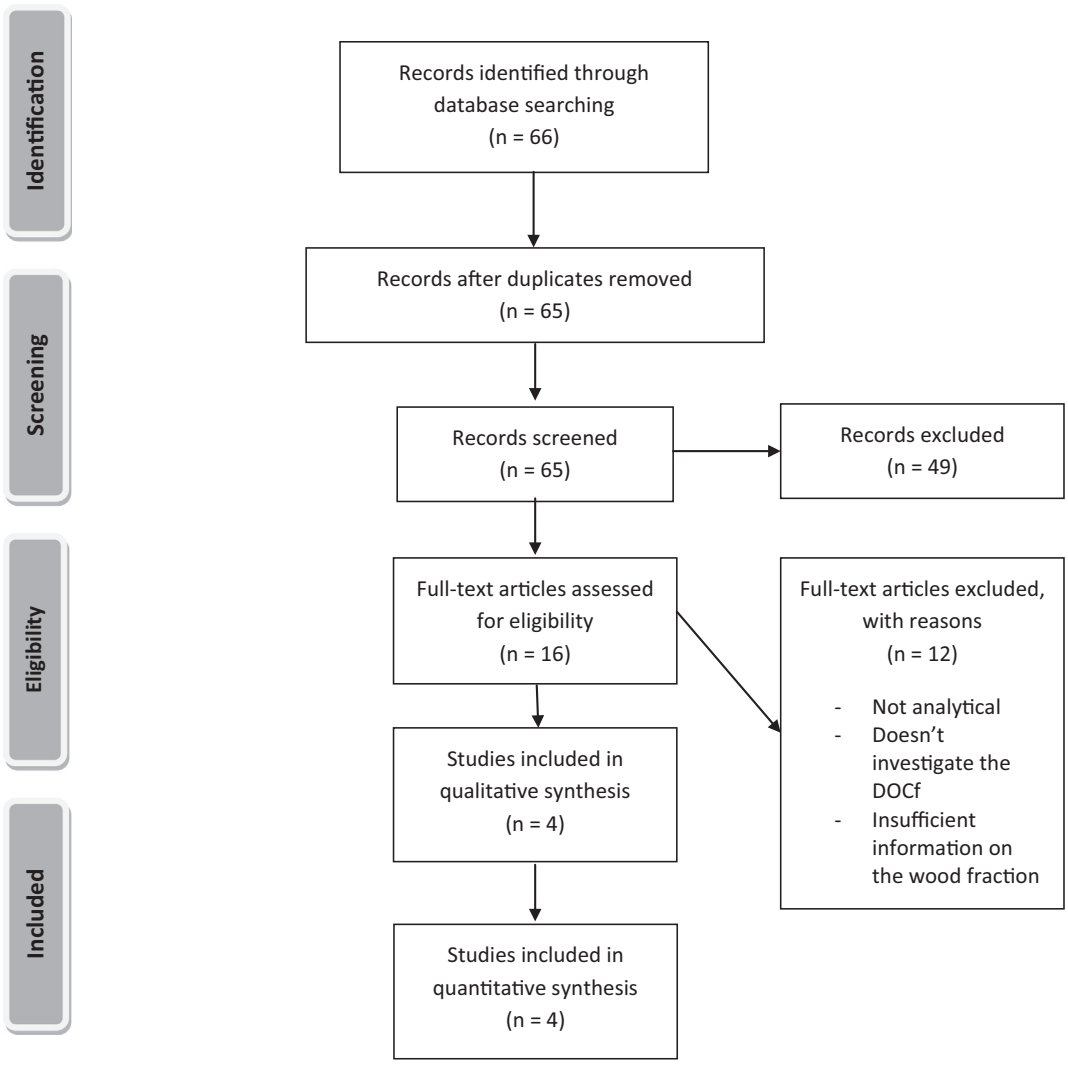
Identification
Screening
Eligibility
Included
Records identified through database searching (n = 66)
Records after duplicates removed (n = 65)
Records screened (n = 65)
Records excluded (n = 49)
Full-text articles assessed for eligibility (n = 16)
Full-text articles excluded, with reasons (n = 12)
- Not analytical
- Doesn't investigate the DOCf
- Insufficient information on the wood fraction
Studies included in qualitative synthesis (n = 4)
Studies included in quantitative synthesis (n = 4)

Fig. 1. Review flow process for the identification of relevant literature for inclusion.

DDOCmaT = DDOCm accumulated in the landfill at end of year T, Gg;
$DDOCma_{T-1}$ = DDOCm accumulated in the landfill at the end of year T − 1, Gg;
$DDOCmd_T$ = DDOCm deposited into the SWDS in year T, Gg;
k = reaction constant (k = ln(2)/t1/2), year − 1; and t1/2 = half life time, year.

$$DDOCm = W \times DOC \times DOC_f \times MCF, \quad (5)$$

where

W = mass of waste deposited, Gg;
DOC = degradable organic carbon in the year of deposition;
DOC_f = fraction of DOC that can decompose (fraction); and
MCF = CH_4 correction factor for aerobic decomposition in the year of deposition (fraction).

Data pertaining to the wood waste (Gg) component of total landfilled waste for the years 1957–2014 was added to the model and the DOC_f was adjusted based on the IPCC default value and values obtained through literature review. The data were then extracted to a new Microsoft Excel database for amalgamation and transformation for analysis.

2.4. Statistical analysis

Prior to statistical analysis, the dependent and independent variables were tested for normality utilising the Shapiro-Wilk test in concurrence with Q-Q plots; all data were found to display a non-normal distribution. Differences between the IPCC default decomposition factor and those derived from literature were assessed using a one-way analysis of variance (ANOVA) to determine and quantify differences between continuous (applied decay rate (quantitative)) and the categorical variables (2 or more groups). To assess the variation within groups, post hoc analysis in the form of the Bonferroni correction was employed. Where there were only two groups, a Mann Whitney U analysis was employed to assess difference in means across the groups. IBM's SPSS Statistics 22 was utilised for all analyses and statistical significance was set at the 95% confidence level ($p < .05$) by convention.

3. Results and discussion

3.1. Summary of literature findings

Upon extensive review, four research papers (Table 1) which adhered to the inclusion criteria and subsequent screening process were assessed in this study. Authorship diversity and thus

Table 1
Summary of literature assessed, DOC_f recorded and methodological approach.

Author	Year	Location	Samples	Avg. DOC_f (Std. Dev)	Methodological approach	Conditions	Notes
Wang and Barlaz	2016	North America	HW (n = 2) SW (n = 2)	0.232 (0.047) (HW) 0.0475 (0.019) (SW)	Landfill simulation (anaerobic) in 8L bioreactor inoculated with decomposed residential waste	Inoculum to sample ratio 1:3 (v/v) ratio. Experiment stopped after no more Ch4 produced ~200 days (SW) – 400 days (HW)	Twig and bough samples were used for each species; DOCf is an average of the two
Ximenes et al.	2015	Cairns, Australia Sydney, Australia	SW (n = 14) HW (n = 18) SW (n = 53) HW (n = 50)	0.018 (0.03)(Sydney) N/A (Sydney) 0.022 (0.03)(Cairns) 0.19 (0.11) (Cairns)	Wood extracted from landfill in situ	**Sydney:** Temp = 12.2–23.3 °C, buried in landfill 44 years. **Cairns:** Temp range = 20.8–29 °C, buried in landfill 16–18 years	Carbon loss averaged across soft and hardwood groups
Wang et al.	2011a,b	North America	SW (n = 2) HW (n = 2) EW (n = 5)	0.009 (0.012) (SW) 0.039 (0.055) (HW) 0.0474 (0.084) (EW)	Landfill simulation (anaerobic) in 8L bioreactor inoculated with decomposed residential waste	Inoculum to sample ratio 1:3 (v/v) ratio. Experiment stopped after no more CH4 produced ~1400 days	Carbon loss averaged across soft, hard and engineered wood (irrespective of wood type) groups
Ximenes et al.	2008	Sydney Park (SP) Landfill and Lucas Heights (LH) Landfill, Australia	HW (n = 25) SW (n = 16) HW (n = 16) SW (n = 21)	0.17 (SP) 0.08 (SP) NA (SW &HW, LH)	Wood extracted from landfill in situ	Samples taken from SP were buried for ≥46 years. Two sites (A and B) at the LH landfill. Site A & B contained material buried for 19 and 29 years at the time of excavation	Carbon loss averaged across soft and hardwood groups within referenced paper, so not S.D derived

HW, Hardwood; SW, Softwood; EW, Engineered Wood.

geographical diversity was low with Wang et al. (2011a,b, 2016) and Ximenes et al. (2008, 2015) each producing two published papers based in North America and Australia, respectively. However, while the volume of research is limited, there is considerable heterogeneity across methodological approach and climatic coverage.

3.1.1. Methodological approach

Studies by Ximenes et al. (2008, 2015) assessed the decomposition of wood products through the extraction of samples in situ and thus provide valuable information pertaining to the reality of landfill decomposition. In contrast, Wang et al. (2011a,b, 2016) assessed wood decomposition through simulation; wood was placed in bioreactor with an inoculum of Municipal Solid Waste (MSW) under landfill conditions and analysed continuously for CH_4 emissions. All studies assessed the degradation of cellulose, hemicellulose and lignin; the major constituents affecting wood waste decomposition. Both author groups also assessed a myriad of wood types with softwood, hardwood and engineered wood products evaluated (Table 2). For softwoods, the predominant species assessed belonged to *Pinus sp.* (n = 11/25, 44%) while others assessed included spruce, larch and additional dominant species. For the hardwoods, Eucalyptus (n = 10/33, 34.5%) was most commonly analysed with Oak (*Quercus* sp.) and several tropical species making up the remainder. All studies included information on the time spent either within landfills or exposed to landfill conditions. Ximenes et al. (2008, 2015) analysed samples which were buried over a range of 16–44 years and thus, offers a broad estimation of decomposition over time. Wang et al. (2011a,b, 2016), as a result of landfill simulation via a bioreactor, allowed the experiment to run until no more CH_4 was produced, or until >95% of potential CH_4 was produced. This timeframe ranged from between approximately 200–1400 days. The combination of both in-situ and simulated analyses allows for comparisons of analytic procedures and can facilitate in guiding further studies into wood degradation in landfills.

3.1.2. Climatic differentiations

As a result of the limited research available pertaining to wood wastes in landfills, variance in climate is also limited, even within their own remit. As the research is contained to both North America and Australia, too large countries (and continent) with highly variable climates, transferability of the results may be limited. However, efforts were made to assess the impact of climate on decomposition and comparisons across the research allow for further elucidation of the effects of temperature, in particular. Research by Ximenes et al. (2015) specifically compared wood decomposition in varying climates. Wood was extracted from two landfill sites in Cairns, and Sydney, Australia. The mean temperature in Sydney ranges from a 12.2 to 23.3 °C, while the mean temperature in Cairns is significantly warmer ranging from 20.8 to 29 °C; allowing for an assessment of climatic influence on landfill decomposition.

3.2. Research findings

3.2.1. Decomposition of hardwoods

In total, 113 samples from 16 hardwood species were analysed. Carbon loss (DOC_f) ranged from 0 to 23.2%, with an average loss of 10.5% across all the samples. The highest C loss (23.2%) occurred under landfill simulated conditions for twigs and boughs (n = 2) (Wang et al., 2016) and thus is primarily representative of yard waste. Ximenes et al. (2015) reported no observable loss of C from hardwood samples (n = 68) extracted from a landfill in Sydney while samples taken from Cairns landfill were reported as having an average C loss of 19%. Microscopic analysis results demon-

Table 2
Overview of wood species assessed within literature by wood type.

Hardwood			Softwood		
Species	*n*	%	Species	*n*	%
Argyrodendron sp.	1	3.4%	*Agathis* sp.	2	8%
Blepharocarya sp.	1	3.4%	*Araucaria* sp.	1	4%
Castanospermum sp.	1	3.4%	*Callitris* sp.	1	4%
Ceratopetalum sp.	1	3.4%	*Chamaecyparis* sp.	1	4%
Dipterocarpus sp.	1	3.4%	*Larix* sp.	2	8%
Doryphora sp.	2	6.9%	*Picea* sp.	2	8%
Eucalyptus sp.	10	34.5%	*Pinus* sp.	11	44%
Flindersia sp.	1	3.4%	*Podocarpus* sp.	1	4%
Gonystylus sp.	1	3.4%	*Pseudotsuga* sp.	2	8%
Grevillea sp.	1	3.4%	*Tsuga* sp.	2	8%
Koompassia sp.	1	3.4%			
Lophostemon sp.	2	6.9%			
Pterygota sp.	1	3.4%			
Quercus sp.	2	6.9%			
Shorea sp.	2	6.9%			
Terminalia sp.	1	3.4%			

strated that fungal decay was prevalent in the samples analysed, suggesting that aerobic decay could account for a proportion of the C loss. However, the authors note that even allowing for C loss as a result of aerobic decay, the decay factors presented are significantly lower than the common default factor of 50% used by the IPCC. Through landfill bioreactor simulation analysis of red oak and eucalyptus by Wang et al. (2011a,b), a C loss of 7.8% and no observable loss for each species respectively, was found, again noting the differentiation between analytically derived C loss and the IPCC default factor. Ximenes et al. (2008) analysed hardwood samples from two landfill sites in Sydney, Australia (Sydney Park and Lucas Heights). The wood samples obtained from the Sydney Park landfill facility (n = 25) were buried for ≥46 years based on the year waste was last accepted. The average loss of C was reported as 17%; similar to results obtained from the Cairn landfill (Ximenes et al. 2015). No observable loss of C was noted from hardwood samples (n = 16) at the Lucas Park landfill facility where the waste had been buried between 19 and 29 years based on newspaper dating. However, it is noted that there were insufficient hardwood samples recovered from one of the sampling sites at Lucas Heights landfill to allow meaningful comparisons between landfills and control samples.

3.2.2. Decomposition of softwoods

In total, 108 samples from 10 softwood species were analysed. Carbon loss (DOC_f) ranged from 0 to 8% with an average C loss of 2.9% across all the samples. A noticeable reduction in average C loss is noted between hardwood and softwood species. This distinction can possibly be explained by the variance of lignin content and structure between hard and soft wood species. Softwoods generally contain a greater amount of lignin which reduces carbohydrate bioavailability; lignin has long been considered unreactive under anaerobic conditions (Colberg, 1988). Furthermore, softwoods contain almost exclusively chemically resistant guaiacyl (G) lignin, whereas hardwoods have more reactive or easily degradable lignins of the guaiacyl (G)-syringyl (S) type (Joshi and Chiang, 2009).

In assessment of the implication of climate on wood product decomposition Ximenes et al. (2015) extracted softwood samples from two landfills in Cairns (n = 53) and Sydney (n = 14), Australia. An average C loss of 1.8% and 2.2% was recorded in Cairns and Sydney, respectively. Interestingly, similar C losses were reported for P. *radiata* and Agathis sp. across both landfills which suggests that climate did not influence decay. Previous assessments substantiate this, suggesting that climatic moisture, temperature, and precipitation should not have a substantial influence on landfill decomposition as all landfills should be capped with an impermeable membrane and covered (Peer et al., 1993). However, it should be noted that this is often not the case. Wang et al. (2011a,b) also assessed decomposition of wood samples from the *radiata* sp. and reported a C loss of 0.1% under landfill simulated conditions; an order of magnitude lower than those reported by Ximenes et al. (2015). This may suggest that the samples from in-situ analysis may have underwent some aerobic decomposition, nevertheless, it must be noted that both values are still far below the IPCC default decomposition factor. Softwood samples taken from the two landfill facilities in Sydney (Sydney Park, n = 16, Lucas Heights n = 21), revealed a C loss of 8% in Sydney Park while no loss was observed in Lucas Heights; similar to HW species. The authors note that heterogeneity in decomposition across the landfill sites is likely as a result of the longer burial time in Sydney Park and potential loss of C due to fungal degradation prior to burial. In the context of the Republic of Ireland, the limited decomposition of softwood species is of particular relevance, with Sitka and Norway spruce accounting for over 56% of forested area, and over 2500 Tonnes of roundwood harvested in 2011 alone (DAFM, 2012).

3.2.3. Decomposition of engineered wood products

Only one study by Wang et al. (2011a,b) assessed the decomposition of engineered wood products under landfill conditions (bioreactor). In assessment, samples of panel board (PB), oriented strand board (OSB), Plywood (PW) and Medium Density Fibreboard (MDF) were exposed to an inoculum of MSW under anaerobic conditions. The C loss varied to between 1.1 and 1.4% for PW, PB and MDF respectively. For the OSB products, both a SW and HW derived sample were assessed with no observable C loss for the SW product, but a C loss of 19.9% for the HW derivative; this further corroborates the need to ascribe differing C decomposition factors for different wood types.

The combined results of all analyses provide an overview of the actual decomposition of wood products in landfills and offer a comparison to default factors utilised through IPCC modelling which is commonly employed. However, substantiation of the implications of utilising these values on national CH_4 emissions from landfills has not been undertaken to date.

3.3. Comparative analysis of the effect of altering DOC_f values on national methane emissions

The IPCC allows the use of country-specific DOC_f values rather than the suggested default values, provided they are based on well documented research (IPCC, 2006). However, investigations into

country and product specific decomposition are both timely and costly and thus unlikely to be undertaken without significant evidence of disparity. As a result, in order to assess the implications of variance between DOC_f values from literature and the IPCC default values, an alternative emissions inventory was created using the IPCC waste model and altering the DOC_f factors.

Using the estimated wood fractions from the national landfill waste tonnage data for the Republic of Ireland, an inventory was created totalling potential CH_4 emissions for the years 1957–2014 under varying decomposition factors. Three scenarios were modelled using softwood, hardwood and engineered wood analysed DOC_f factors from literature and the IPCC default (0.5). For all scenarios, the following assumptions were made:

(1) Wood wastes in landfills are homogenous (i.e. all softwood, hardwood or engineered wood and,
(2) The ratio of methane to carbon dioxide emissions is 1:0, i.e. no carbon dioxide emissions result (anaerobic environment).
(3) No methane recovery takes places.

As a consequence of these assumptions, the results are representative of the worst case scenario, but allow for a valuable assessment across wood types and the resulting carbon emissions; offering a baseline reconnaissance into the decomposition of wood products in landfills at a national level. The assumption that no methane recovery takes place is to account for the fact that an EPA report in 1997 demonstrated that only 15% of landfill sites in Ireland were flaring or utilising landfill gas (McCarthy et al., 2010).

3.3.1. Scenario 1: Decomposition of softwoods in landfills

Under scenario one, the wood fraction of total landfill waste is assumed to contain only softwood species of wood. The default DOC_f factor of 50% as recommended by the IPCC was firstly applied to the data followed by the DOC_f factors obtained from literature. In total, 6 total CH_4 emissions simulations were calculated (Fig. 2) and summed to represent the total CH_4 emissions across all 6 scenarios. Under the IPCC default factor 119,232 Tonnes of CH_4 was generated. Contrastingly, when the IPCC DOC_f factor was substituted with values obtained from literature, the total CH_4 emissions varied from a minimum of 2,118 (S.D = ±2,870) Tonnes to a maximum of 21,578; 6 to 56 times less than the IPCC default.

To quantify a statistically significant difference across the factors, a Oneway-ANOVA analysis of variance was undertaken with post-hoc analysis (Bonferroni) employed to assess differences within the groups. A significant difference ($F = 45.362$, $p = <.001$) was found to exist between the IPCC default factor and all other values derived from literature. Interestingly, however, there was no significant difference found to exist between the values obtained solely through literature. This suggests that for softwood species in landfills, the decomposition, when assessed either by in-situ analysis or landfill simulation does not display significant variances. The results also support that climatic variation and even time spent in landfill may not play a key role in softwood product decomposition in an anaerobic environment.

3.3.2. Scenario 2: Decomposition of hardwoods in landfills

Under scenario two, the wood fraction of total landfilled waste is assumed to contain only hardwood species of wood. As with the previous scenario, the DOC_f factor of 50% as recommended by the IPCC was firstly applied as a benchmark followed by the DOC_f factors obtained from literature. In total, 5 total CH_4 emissions simulations were calculated (Fig. 3). The IPCC emissions remain the same as in scenario one, while the total CH_4 emissions varied from a minimum of 5178 (S.D = ±7342) Tonnes of CH_4 to a maximum of 55,124 (S.D = ±11,323) Tonnes of CH_4; considerably higher emissions than from the homogenous softwood scenario. However, the CH_4 emissions calculated for scenario two still remain between 2 and 13 times less than the IPCC default decomposition factor for wood.

Statistically, a significant difference ($F = 20.691$, $p = <.001$) was still found to exist between the IPCC default factor and all other values derived from literature. However, in this scenario, a significant difference ($p = .044$) between the 2016 and 2011 studies by Wang et al. also exists. Although, it must be noted that the study

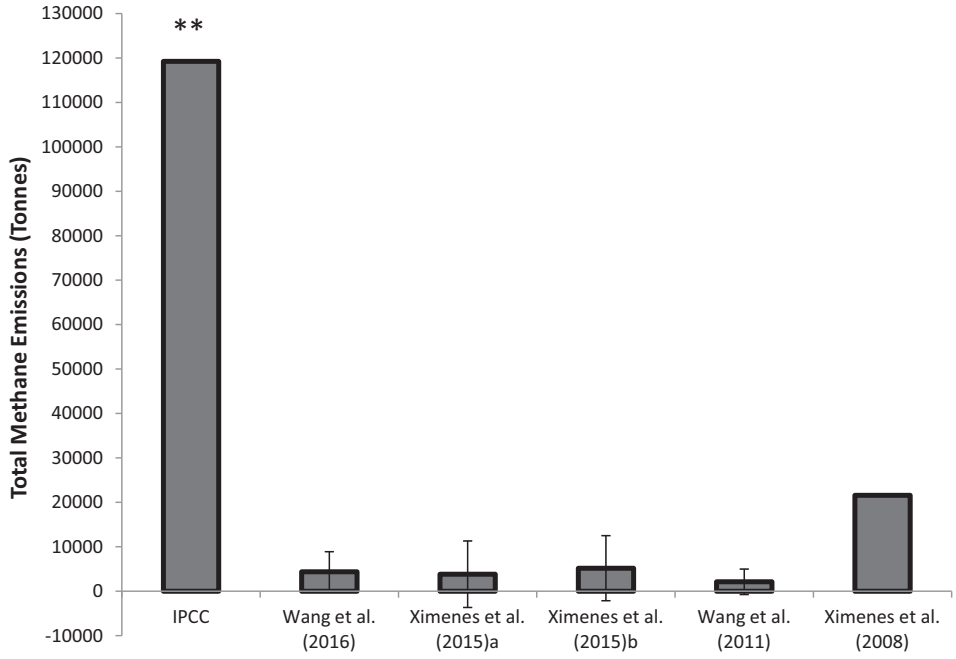

Fig. 2. Total CH_4 emissions from the wood fraction of landfilled waste (1957–2014) from softwood species under varying DOC_f factors. **Denotes statistical significance at the $p < .001$ level. [a]Sydney [b]Cairns.

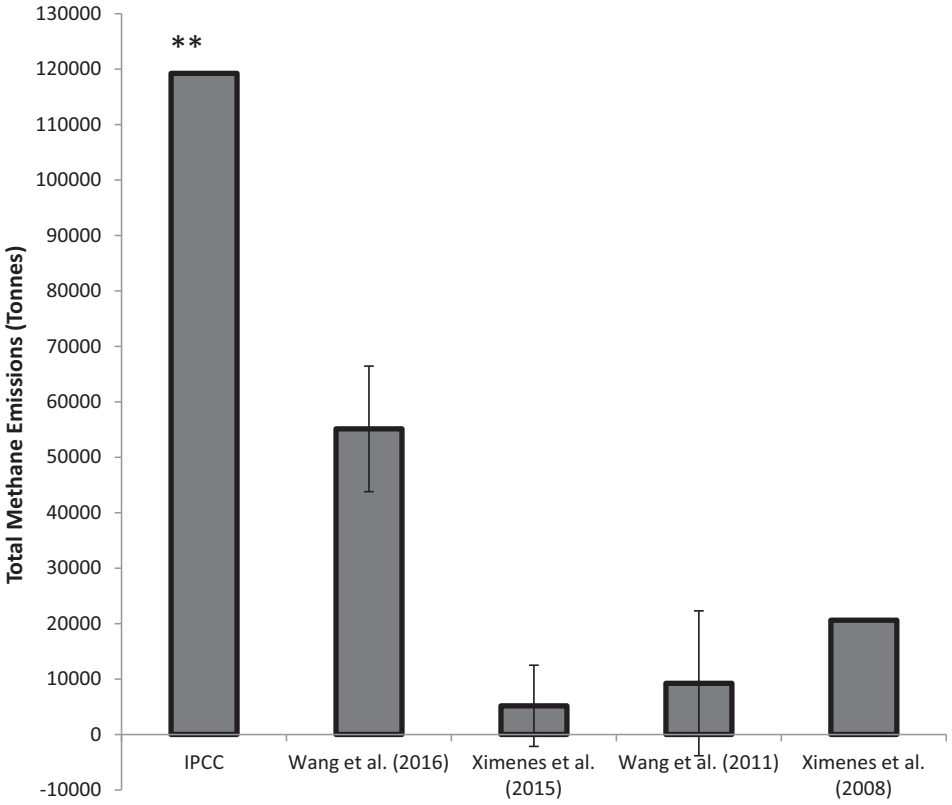

Fig. 3. Total CH_4 emissions from the wood fraction of landfilled waste (1957–2014) from hardwood species under varying DOC_f factors. **Denotes statistical significance at the $p < .001$ level.

by Wang et al. (2016) focused on smaller fractions of wood waste (twigs) and thus, these may have decomposed at a quicker rate. However, results still suggest that similar to softwood species, the decomposition of hardwoods in landfills does not vary significantly respective of climate, methodology or time.

3.3.3. Scenario 3: Decomposition of engineered woods in landfills

Only one study (Wang et al., 2011a,b) assessed the decomposition of engineered wood in a landfill environment (bioreactor). In total, four engineered wood products were assessed with large variations between PW, PB and MDF; which had little observable carbon loss and the OSB products, for which there was a SW and HW representative. As there was limited data availability, the average decomposition factor across all products was applied to the wood waste data. Therefore, the CH_4 emissions reported here will have a high standard deviation and are a conservative estimation. Total CH_4 emissions from EW were calculated at 13,997 Tonnes over the reporting period; 9 times greater than emissions estimated using the IPCC default decomposition factor. As with the other scenarios, a statistically significant difference ($U = 4.726$, $p = <.001$) was found to exist between the two factors; again supporting the hypothesis that the IPCC factor is a gross overestimation of the decomposition of wood products in landfills.

3.3.4. Implications and limitations of findings

The results outlined here provide strong evidence to support that the rate and extent of decomposition of wood products in landfills is likely overestimated by the IPCC. If substantiated on a national level, landfill waste emission calculations at a higher tier will aid the development of more accurate GHG emission inventories. In addition, this research further substantiates that a significant portion of the biogenic C in wood products in landfill does not decompose, and therefore represents a sink of C storage in landfills (Eleazer et al., 1997, Wang et al., 2011a,b, Barlaz, 2004, Barlaz, 1998). However, this is not to suggest that landfilling, which is at the bottom of the waste hierarchy, is a viable alternative method of C sequestration. Rather, emphasis should be placed on the diversion of wood products from landfill and through cascade utilization, maximize the socio-economic advantage that can be collected from a limited amount of wood by increasing the efficiency of its use and reuse over time(Haberl and Geissler, 2000). Aside from the environmental considerations of the decomposition, the results of this study also provide valuable information for CH_4 recovery. Research has shown that CH_4 yields from landfill sites are often lower than predicted through modelling (Barlaz et al., 1990, Augenstein and Pacey, 1991, Bogner, 1992). The low decomposition of wood products in landfills may help to explain this discrepancy and facilitate in the calibration of models used to predict recoverable CH_4.

The limitations of this study are mainly derived from the low frequency of applicable research and thus, there is a need to promote further research in this area. Within the research that is available, however, there are also limitations. As noted by the authors, there is, as of yet, insufficient in situ field evidence to determine what proportion of C from wood products is emitted as carbon dioxide (CO_2) and as CH_4. The true greenhouse impact of wood products in landfills will depend on how much carbon is released as CH_4 (taking into account C recovery, and C oxidation), which has a global warming potential 28 times that of CO_2. There are also knowledge gaps pertaining to engineered wood products, which likely constitute a substantial proportion of the waste supply, and due to preservation techniques may degrade even slower. Similarly, the segregation of waste to specifically quantify engineered wood is limited, and thus estimation of volumes diverted

to landfills is difficult. It should also be noted that this paper solely investigated wood wastes, and thus the DOCf of other organic materials has not been investigated. The IPCC recommends a DOCf of 0.77 for non-lignin containing organic waste and thus, a mixed waste stream with a DOCf of 0.5 applied may potentially 'correct' the error for wood wastes within the landfill. However, this research has presented DOCf values as small as zero for wood wastes, and thus, even allowing for larger DOCf values within other organic waste streams, is cause for further investigation. Finally, as stated previously, the wood fraction of Irish landfilled waste was assumed to be homogenous; this is a false assumption. However, without accurate waste stream catalogues, this approach provides the most conservative estimation to guide future research; improved waste stream characterisation will improve emission reporting.

4. Conclusion

This is the first study to systematically review and statistically assess the implications of variation of wood decomposition rates on national GHG emissions from landfills. The results demonstrate that CH_4 emissions from the wood fraction of landfilled waste are likely overestimated by countries utilising the IPCC DOC_f default factors. Through the development of alternative emission inventories and statistical analysis, this study showed that while there is a significant difference between the IPCC and analytical derived DOC_f factors, there is no significant difference between the analytical factors. As a result, it can be substantiated that climate and landfill specific conditions do not significantly alter the decomposition rates of wood products in landfills. In conclusion, there is sufficient evidence to warrant further investigations into wood product decomposition at a national level and promote emission reporting at a higher tier. Utilisation of country specific DOC_f factors may have significant consequences on national GHG balances, particularly where there has been an historic reliance of landfills.

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